

# GAMMA RAY BURST ENGINE ACTIVITY WITHIN THE QUARK NOVA SCENARIO: PROMPT EMISSION, X-RAY PLATEAU, AND SHARP DROP-OFF

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*Draft version February 2, 2008*

## ABSTRACT

We present a three-stage model for a long GRB inner engine to explain the prompt gamma ray emission, and interpret recent Swift satellite observations of early X-ray afterglow plateaus followed by a sharp drop off or a shallow power law decay. The three stages involves a neutron star phase, a quark star (QS) and a black hole phase as described in Staff et al. (2007). We find that the QS stage allows for more energy to be extracted from neutron star to QS conversion as well as from ensuing accretion onto the QS. The QS accretion phase naturally extends the engine activity and can account for both the prompt emission and irregular early X-ray afterglow activity. Following the accretion phase, the QS can spin-down by emission of a baryon-free outflow. The magnetar-like magnetic field strengths resulting from the NS to QS transition provide enough spin-down energy, for the correct amount of time, to account for the plateau in the X-ray afterglow. In our model, a sharp drop-off following the plateau occurs when the QS collapses to a BH during the spin-down, thus shutting-off the secondary outflow. We applied our model to GRB 070110 and GRB 060607A and found that we can consistently account for the energetics and duration during the prompt and plateau phases.

*Subject headings:* gamma rays: bursts, stars: evolution

## 1. INTRODUCTION

Observations of Gamma ray bursts (GRBs) by the SWIFT satellite (Gehrels et al. 2004) have revealed that many GRBs show a flat segment in their early X-ray afterglow. This flat segment is often observed to start after about  $10^3$  seconds, and lasts up to  $10^5$  seconds. Following the plateau, some afterglows decay following a power law with a modest power of about  $-1$  to  $-2$ . However, in some cases a very sharp drop-off succeeds the plateau.

In the literature, there are mainly two different explanations for the flattening that have been proposed: (i) the refreshed shocks explanation (Rees & Mészáros 1998), where slower shells ejected during the prompt engine phase catch up with the external shock and refresh it. The plateau is then followed by a shallow decay of power index  $-1$  to  $-2$  from the cooling of the external shock once the shells stop hitting it; (ii) Extended engine activity in the form of a secondary outflow (see for example Panaitescu 2007). The secondary outflow explanation requires that the engine is active for longer than previously expected, and so if the engine in fact turns off at a later time it can provide an explanation for the sharp drop-off in the observed light curve.

In this paper we appeal to a secondary outflow, and propose that it is emitted by a quark star (QS; specifically a color-flavor locked strange QS with no crust; Ouyed et al. 2005). This secondary outflow leads to the observed flattening, and the sharp drop-off we argue is a consequence of the cessation of the secondary outflow from the transition of the QS (the GRB inner engine in our model) to a black hole (BH). In a previous

paper (Staff et al. 2007, hereafter SOB07), a three stage model for long GRBs was suggested, involving a neutron star (NS) phase, followed by an accreting QS phase and a plausible third stage that occurs when the QS accretes enough material to become a BH. The advantages of our model is that, by including a QS phase, we can account for both energy and duration of the prompt emission, the flattening, the sharp drop-off or shallow decay, and the X-ray flaring (see SOB07).

The secondary outflow is a pair wind due to spin-down from magnetic braking of the QS (Niebergal et al. 2006). Here we suggest that the rotational energy of a rapidly rotating QS can be used to explain the flattening. This paper is organized as follows: In section 2 we briefly describe the framework of our model. In section 3 we discuss how the rotational energy released as the QS spins down due to magnetic braking can give rise to flattening in the X-ray afterglow. Also, the sharp drop-off is discussed as a signature of the QS turning into a BH. In section 4 we apply our model to GRB 070110 and GRB 060607A. We summarize and conclude in section 5.

## 2. THE THREE STAGES

The three stages of the GRB engine described in SOB07 are as follows. Stage 1 is a (proto-) NS phase, the NS being born in the collapse of the iron core in an initially massive star. This NS can collapse to a QS, either by spin-down (Staff et al. 2006) or through accreting material, thereby increasing its central density sufficiently that it can form strange quark matter. We suggested that this stage could lead to a delay between the core collapse and the GRB. The collapse into a QS, in a quark nova (QN; Ouyed et al. 2002; Keränen et al. 2005), releases up to  $10^{53}$  ergs that might help power the explosion of the

star. This can possibly explain why GRBs associated with supernovae are often very energetic (see Ouyed et al. 2007; Leahy & Ouyed 2007). If a QS is formed directly in the core collapse, stage 1 will be bypassed and the process starts from stage 2.

Stage 2 is accretion onto the QS from the surrounding hyperaccreting debris disk, which is formed from material left over from the collapse of the progenitor. This launches a highly variable ultra-relativistic jet, in which internal shocks can give rise to the gamma radiation seen in a GRB (Ouyed et al. 2005). This jet will eventually interact with the surrounding medium creating an external shock that gives rise to the GRB afterglow. The afterglow light curve would follow a powerlaw  $F_\nu \sim t^{-(1-2)}$  (Sari et al. 1998). However, slower shells can catch up with the external shock at later times and refresh it. This can lead to a flatter segment in the X-ray afterglow (e.g. Rees & Mészáros 1998) which is commonly seen in GRB afterglows (O’Brien et al. 2006; Liang et al. 2007).

Stage 3, which occurs if the QS accreted sufficiently that it collapsed to a BH, is accretion onto the BH which launches another ultra-relativistic jet, as described in De Villiers, Staff, & Ouyed (2005). Interaction between this jet and the QS jet or internal shocks in the BH jet itself can give rise to flaring commonly seen in the X-ray afterglow of GRBs. The BH jet has the potential to be very powerful, so if it catches up with the external shock a bump might be seen in the light curve. The relevant features and emission have been discussed in details in SOB07. Alternatively, if the QS did not collapse to a BH, continued accretion onto the QS after the prompt phase might also be able to explain X-ray flaring.

### 3. PROMPT EMISSION, X-RAY PLATEAU, AND SHARP DROP-OFF

In our model the prompt emission is produced by internal shocks in a QS jet launched by hyperaccretion onto a QS (Ouyed et al. 2005). In this section we will first explain that for the accreting material to be channeled to the polar cap region, this requires a very high magnetic field. If the QS survives the accretion and is rapidly rotating, this magnetic field can then spin the QS down. We will show that a similarly strong magnetic field is what is needed to get the right spin-down time to explain the observed flattening.

#### 3.1. Prompt Emission

The prompt gamma ray emission corresponds to synchrotron emission by electrons accelerated in internal shocks in the QS jet. This jet forms an external shock upon interacting with the surrounding medium, and synchrotron emission from this external shock is responsible for the afterglow.

In order to explain the energy observed in the prompt gamma radiation, SOB07 found that the accretion rate onto the QS must be of the order  $\dot{M} \sim 10^{-5} - 10^{-3} M_\odot/\text{s}$ . In order to create a jet, the accretion has to be channeled onto the polar cap. This can occur if the magnetic radius is at least twice the radius of the star. With the before mentioned accretion rate, a magnetic field of the order  $B \sim 10^{14} - 10^{15} \text{ G}$  (see Ouyed, Keränen, & Maalampi 2005) is required.<sup>1</sup> It should be noted that this QS jet

is much different than the typical MHD disk wind jets. A QS jet is created as the accreting material reaches the surface of the QS, it is converted into CFL quark matter, resulting in the creation of a hot spot due to the release of excess binding energy. This region cools by emitting photons, which collide with subsequent accreting material, resulting in the ejection of material with high Lorentz factors (for details, see Ouyed et al. 2005).

Given that the prompt emission requires such high magnetic fields (because of the high accretion rates), one has to reconcile this with the plateaus observed in some light curves at later times.

A very high magnetic field and a high accretion rate can make the QS find itself in the propeller regime if it is also spinning very fast ( $P \lesssim 2 \text{ ms}$ ). If the QS is born in the propeller regime, then we suggest that there will be a delay between the formation of the QS and the launching of the jet, while the propeller spins the QS down.

#### 3.2. Flattening

Panaiteescu (2007) suggested that an outflow, ejected by the engine after the initial blast, can scatter the forward-shock synchrotron emission and thereby produce flux that will outshine the primary one, especially if the outflow is nearly baryon free and highly relativistic<sup>2</sup>. This reflected flux can produce certain light-curve features such as flares, plateaus, and chromatic breaks. For this to occur, the duration of this scattering outflow has to last as long as these observed features (modulo cosmological time-dilation).

We next show that by using the rotational energy lost from a QS spinning down, assuming a magnetic field of  $10^{15} \text{ G}$ , a spin-period of  $\sim 2 \text{ ms}$ , a characteristic decay time of the order  $10^3 - 10^4$  seconds is obtained. The observed flattening in the light-curves of certain GRBs can last for several times  $10^4 \text{ s}$  and fits well with the duration from the QS spin-down.

Following the birth of a CFL QS, due to the onset of color superconductivity the magnetic flux inside the star is forced into a vortex lattice that is aligned with the rotation axis. This subsequently forces the magnetic field outside the star to re-structure itself into a dipole configuration that is aligned with the rotation axis (Ouyed et al. 2006). Such an aligned rotator will spin down by magnetospheric currents escaping through the light cylinder. Pair production from magnetic reconnection supplies these currents (Niebergal et al. 2006) with a corresponding luminosity given by (Shapiro & Teukolsky 1983):

$$L = -\dot{E}_{\text{rot}} \sim \frac{B^2 \Omega^{(n+1)} R^6}{c^3}, \quad (1)$$

where  $B$  is the magnetic field at the pole,  $R$  is the radius of the star,  $\Omega$  is the angular rotational frequency of the star,  $c$  is the speed of light,  $n$  is the magnetic braking index.

For an aligned rotator without field decay, the braking index is roughly  $n \sim 3$ , however due to magnetic flux

obtained during QS formation due to the response of quarks to the spontaneous magnetization of the gluons (e.g. Iwazaki 2005, and references therein).

<sup>2</sup> An alternative model for generating the radiation is magnetic reconnection or dissipation processes in a highly magnetized outflow which was proposed by Usov (1994, for the prompt emission) and Gao & Fan (2006, for the afterglow).

<sup>1</sup> Recent work shows that  $10^{15} \text{ G}$  magnetic fields can readily be

expulsion from a CFL QS, the magnetic field decays as prescribed by Niebergal et al. (2006). This results in an evolution of the luminosity due to spin-down, which is expressed by the relation,

$$L \sim 3.75 \times 10^{48} \text{ erg s}^{-1} \left( \frac{B_0}{10^{15} \text{ G}} \right)^2 \left( \frac{2 \text{ ms}}{P_0} \right)^4 \left( 1 + \frac{t}{\tau} \right)^{-5/3} \quad (2)$$

where the characteristic spin-down time (in seconds) is,

$$\tau = 3.5 \times 10^3 \text{ s} \left( \frac{10^{15} \text{ G}}{B_0} \right)^2 \left( \frac{P_0}{2 \text{ ms}} \right)^2 \left( \frac{M_{\text{QS}}}{1.4 M_{\odot}} \right) \left( \frac{10 \text{ km}}{R_{\text{QS}}} \right)^4 \quad (3)$$

In the above equations,  $M_{\text{QS}}$  is the QS mass,  $P_0$  is the initial spin period, and  $B_0$  is the initial magnetic field strength.

From Eq. 2 one can see that the luminosity, due to rotational energy extracted from spin-down of a QS, has a natural break at time  $\tau$ . Thus, if there was a one to one relationship between spin-down luminosity and observed emission, then the power law decay of the observed light-curve should change from zero to  $-5/3$  after roughly ten thousand seconds. However, the observed emission might be modified by the forward shock as discussed in Panaitescu (2007).

The energy released from the spin-down of the QS is likely to be in the form of an  $e^+e^-$  wind. Thus, it should be mostly baryon free, since the QS becomes bare immediately following its birth as it enters the CFL phase (see Niebergal et al. 2006). As in the case of a pulsar, spin-down energy extracted from a QS is mainly in the equatorial plane. Bucciantini et al. (2007) performed numerical simulations where they showed that it is still possible to collimate such equatorial flows into a jet.

A relativistic outflow from the spin-down of a highly-magnetized *neutron* star has been suggested before as a mechanism to produce plateaus (for instance in Troja et al. 2007), however they did not propose a unified model explaining both the prompt emission and the afterglow features. We have here proposed a model that can explain both the prompt GRB emission and the observed X-ray afterglow features.

### 3.3. Sharp vs. Gradual decay

Eq. 2 naturally gives a break in the engine luminosity at  $t = \tau$ . The engine will also remain active after this break, but the engine luminosity will gradually decay (with a power law  $\sim -5/3$ ; which is not necessarily the power law decay in the observed emission). In some instances however, it is possible that the QS reaches an unstable configuration, such that the QS stage is only temporary before the collapse to a BH.

If the QS collapses to a BH during spin-down, the engine will likely be shut off. Although the BH is likely to be rapidly rotating, a disk is necessary in order to extract the rotational energy of a BH through the Blandford-Znajek mechanism (BZ; Blandford & Znajek 1977). Only if a disk has remained around the QS during spin-down or if it is formed after the formation of the BH, can the BZ mechanism play a role. If this does not occur, the observed light curve will be generated by the external shock only after this stage. A sharp drop off will be seen as the light curve drops from the level given by the spin-down outflow to the level given by the external shock.

TABLE 1  
OBSERVED QUANTITIES IN GRB 070110 AND GRB 060607A.

	GRB 070110	ref	GRB 060607A	ref
redshift ( $z$ )	2.352	†	3.082	†
$E_{\text{iso},X}$	$1.85 \times 10^{52}$ ergs	†	$6.16 \times 10^{52}$ ergs	†
$T_{\text{break}}$ (engine frame)	6000 s	‡	2750 s	‡
$L_{\text{Obs.,iso}}$ (during plateau)	$10^{48}$ erg/s	♣	$6 \times 10^{48}$ erg/s	♠
$L_{\text{Eng.,10}}$ (during plateau)	$1.5 \times 10^{46}$ erg/s	◇	$1 \times 10^{47}$ erg/s	◇
$T_{90}/(1+z)$	25.4 s	‡	24.5 s	‡
$E_{\gamma,\text{iso}}$	$2 \times 10^{52}$ ergs	†	$5.2 \times 10^{52}$ ergs	†
$E_{\gamma,10}$	$1.0 \times 10^{50}$ ergs		$2.5 \times 10^{50}$ ergs	

References:

†: Liang et al. (2007)

‡: Calculated using redshift and duration from Liang et al. (2007)

♣: Troja et al. (2007)

♠: Calculated using  $E_{\text{iso},X}$ ,  $z$ , and  $T_{\text{break}}$  from Liang et al. (2007)

◇: Observed luminosity corrected for redshift, assuming 10 degrees opening angle

We suggest that in GRB light curves exhibiting plateaus, those possessing a gradual decay following the plateau are either due to refreshed shocks as discussed in SOB07 or from spin-down of QSs that have not collapsed to BHs. If the secondary outflow is responsible for the X-ray afterglow, then the external shock can produce the optical afterglow. This scenario might explain why the optical and X-ray afterglows behave different in some GRBs.

## 4. CASE STUDY

In this section we will apply our model to two GRBs, GRB 070110 and GRB 060607A, that both show a flattening followed by a sharp drop off which is difficult to explain with the external shock. Some observed properties of both GRBs are summarized in Table 1.

Based on observations of the duration of the X-ray flattening, we use Eq. 3 to estimate the corresponding magnetic field strength. We then use Eq. 2 to find the spin-down luminosity. Both the magnetic field and the spin-down luminosity found this way are listed in Table 2 which is then compared to observed values (Table 1). Furthermore, now that we have an estimate for the magnetic field of the QS, this gives us an estimate for the accretion rate that can be channeled to the polar cap. We assume a jet opening angle of about 10 degrees. The observed prompt GRB emission is then calculated by assuming that a combination of accretion efficiency and radiative efficiency leads to  $\sim 1\%$  of the total gravitational energy of the accreted material is converted to prompt radiation. As shown below, for both GRB 070110 and GRB 060607A we find that the magnetic field found based on the duration of the X-ray flattening consistently and simultaneously explains the energy of both the GRB itself and the X-ray flattening.

In our model we know the time at which the QS collapses to a BH (the time of the steep decay). The calculations above assumed that this occurred at  $t_{\text{collapse}} = \tau$ . However, it could also occur at  $t_{\text{collapse}} < \tau$ , which implies that the magnetic field is weaker than found above. Hence, the magnetic field found above is the maximum possible magnetic field, and therefore the spin-down luminosity, accretion rate and prompt gamma ray energy are also maximum.

TABLE 2  
DERIVED QUANTITIES FOR GRB 070110 AND GRB 060607A.

	GRB 070110	GRB 060607A
Maximum magnetic field	$6.8 \times 10^{14}$ G	$1.0 \times 10^{15}$ G
Spin-down luminosity	$1.6 \times 10^{48}$ erg/s	$3.6 \times 10^{48}$ erg/s
$\dot{m}_{\text{acc.,max.}}$	$7.5 \times 10^{-4} M_{\odot}/\text{s}$	$1.6 \times 10^{-3} M_{\odot}/\text{s}$
$E_{\gamma,10,\text{max}}$	$3.8 \times 10^{50}$ ergs	$7.8 \times 10^{50}$ ergs
$E_{\gamma,\text{iso,max}}$	$7.9 \times 10^{52}$ ergs	$1.6 \times 10^{53}$ ergs

The maximum magnetic field is calculated using Eq. 3 assuming that the QS collapsed to a BH at  $t = \tau$  and an initial spin period of 2 ms. The other quantities in this table is calculated based on this maximum magnetic field.

#### 4.1. GRB 060607A and 070110

The QS magnetic field needed to explain the flattening observed in GRB 070110 is  $B = 6.8 \times 10^{14}$  G (see Table 2). The corresponding spin-down luminosity is found to be  $1.6 \times 10^{48}$  erg/s. We can compare this to the observed engine luminosity assuming an opening angle of 10 degrees for this outflow. If we assume an efficiency of 10% in converting kinetic energy to photons we see that we have an order of magnitude more energy than needed. Comparing the observed prompt gamma ray energy to what we find from the jet launched by the QS, we again find that the jet energy is higher (by a factor 4) than the observed gamma ray energy.

The QS magnetic field needed to explain the flattening observed in GRB 060607A is  $B = 1 \times 10^{15}$  G (see Table 2). The corresponding spin-down luminosity is found to be  $3.6 \times 10^{48}$  erg/s. Assuming 10% efficiency in producing X-ray photons, we find (as for GRB 070110) that the estimated luminosity is higher than the observed. The gamma ray energy released during the prompt phase is also higher than the observed gamma ray energy.

The higher luminosities can be because the estimate for the magnetic field is too high, meaning that  $\tau$  is larger and that the QS collapsed to a BH before  $t = \tau$ . A lower magnetic field implies that the accretion rate is lower. Alternatively, we have overestimated the efficiencies, or the opening angle of the outflow is larger.

In GRB06067A there are several X-ray flares observed until about 300 seconds (about 75 seconds when corrected for redshift). If we explain these flares by accretion onto the QS as well, that means that the accretion process lasts for about 75 seconds. The derived accretion rates imply the necessity of a debris disk with a mass of the order of  $\sim 10^{-1} M_{\odot}$ , which is reasonable since the QN goes off inside a collapsar, where such a large fall-back disk is in principle allowed.

## 5. SUMMARY & CONCLUSION

We have presented a model to explain the flattening and occasional sharp drop-off seen in X-ray afterglows of some GRBs. Our model borrows the framework of the 3 stage model presented in SOB07 which makes use of an intermediate QS stage between the NS and the BH. By appealing to a secondary outflow, from the QS spin-down due to magnetic braking, our model seems to explain the GRB itself (i.e. prompt emission), the observed flat segment (i.e. plateau), and the subsequent sharp or gradual decay following the plateau. The sharp or gradual decay depends on whether the QS collapses to a BH or not during spin-down. During spin-down, a break will be seen after a characteristic time  $\tau$  given by Eq. 3 followed by a power law with power of  $-5/3$  to  $-3$  (Panaitescu 2007). A very sharp drop-off will be seen if the QS collapses to a BH during spin-down.

We note that, if there was a way for launching ultra-relativistic jets from accretion onto NSs, then it would be tempting to not include the QS phase in our model and appeal only to NS to BH transition. However, we are not aware of any such mechanism for launching an ultrarelativistic jet from accretion onto a NS, and from an energetics perspective it seems unlikely. Hence, the additional energy available from converting hadronic to strange quark matter and during accretion onto the QS seems crucial in explaining the nature of GRBs.

In addition to an energetics point of view, the most important benefits of our GRB model involving a QS stage are: (i) the QS offers an additional stage that allows for more energy to be extracted from the conversion from NS to QS as well as from accretion. Also, additional energy is released as the QS quickly evolves from a non-aligned to an aligned rotator following its birth with up to  $10^{47}$  ergs released in a few seconds (Ouyed et al. 2006). As such, the QS phase extends the engine activity and so can account for both the prompt emission and irregular X-ray afterglow activity; (ii) a natural amplification of the NS magnetic field to  $10^{14}$ - $10^{15}$  G during the transition to the QS (Iwazaki 2005). Such high strengths gives the correct spin down time to for the plateau; (iii) since QS in the CFL phase might not have a crust, the spin down energy will most likely be extracted as an  $e^+e^-$  fireball with very little baryon contamination (see discussion in Niebergal et al. 2006). Panaitescu (2007) favors a baryon free secondary outflow to explain the plateau.

We thank Y. Fan and D. Xu for comments.

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